APPENDIX C

DESIGN EXAMPLES

C-1. Problem. Determine maximum elevation of culvert at filling valves for cavitation-free operation.

EXAMPLE 1

C-2. Data Previously Developed.

Upper pool - el 160
Lower Pool - el 120
Lift - 40 ft
Lock Chamber - 670 ft by 110 ft
Two Culverts
Valves 12.5 by 12.5 ft
Loss Coefficients for Filling

Intake	0.200 $V^2/2g$
Upstream conduit	0.050 $V^2/2g$
Downstream conduit	0.380 $V^2/2g$
Chamber manifold	1.000 $V^2/2g$
Total (valve open)	1.730 $V^2/2g$

C-3. Solution.

a. Develop Hydraulic Data. Assume culvert roof at filling valves at el 115 and no roof expansion downstream from the valves. (This is the maximum elevation permissible dictated by criterion of 5 ft of submergence of the culvert system at lower pool.) Use computer program (Appendix B) to develop hydraulic conditions during filling. Data from these computations pertinent to this example are listed in table C-l.

Table C-l

				At Vena Contracta	
Time min	Valve Open %	Contraction Coefficient	Inflow cfs	Pressure Gradient el	Pressure on Culvert Roof, ft
0.0	0.000	0.800	0	120.0	5.00
0.1	0.025	0.799	322	118.6	3.61
0.2	0.051	0.795	650	118.4	3.37
0.3	0.077	0.788	991	117.9	2.94
0.4	0.106	0.778	1,350	117.2	2.25

(Continued)

Table C-1 (Continued)

Time min	Valve Open %	Contraction Coefficient	Inflow cfs	At Vena Contracta: Pressure Gradient el	At Vena Contracta: Pressure on Culvert Roof, ft
0.5	0.137	0.763	1,731	116.2	1.22
0.6	0.171	0.744	2,138	114.7	-0.30
0.7	0.207	0.720	2,554	113.2	-1.76
0.8	0.248	0.690	2,928	113.1	-1.90
0.9	0.292	0.656	3,375	110.2	-4.78
1.0	0.340	0.651	3,916	109.6	-5.39
1.1	0.392	0.655	4,565	108.9	-6.06
1.2	0.448	0.664	5,326	107.8	-7.20
1.3	0.507	0.677	6,188	106.8	-8.18
1.4	0.571	0.695	7,117	106.7	-8.29
1.5	0.637	0.718	8,053	108.1	-6.88
1.6	0.706	0.747	8,918	111.3	-3.67
1.7	0.777	0.780	9,641	116.1	1.13
1.8	0.851	0.818	10,179	121.8	6.83
1.9	0.925	0.858	10,530	127.6	12.61
2.0	1.000	0.900	10,746	132.7	17.74

b. Determine Minimum Value of Cavitation Parameter, K . From consideration of pressures in table C-l, it appears that K should be minimum within the time period of 1.2 to 1.5 min. Thus, from data in table C-l:

Table C-2

Time min	Valve Open ft	At Vena Contracta: Depth-† ft	At Vena Contracta: V†† fps	At Vena Contracta: $V^2/2g$	At Vena Contracta: P‡ ft	K See para 2-2b
1.2	5.60	3.72	57.29	50.97	1.58	0.678
1.3	6.34	4.29	57.69	51.68	0.03	0.639
1.4	7.14	4.96	57.39	51.14	-0.75	0.631
1.5	7.96	5.72	56.34	49.29	-0.10	0.668

† Valve open in feet times contraction coefficient.
†† Inflow divided by product of number of culverts (2) times width of a culvert (12.5 ft) times depth at vena contracta.
‡ Pressure on culvert roof plus depth of culvert (12.5 ft) minus depth at vena contracta.

Since the minimum valve of K , 0.631 , is less than K_i 1.000 (fig. 2-1) the culvert must be lowered or expanded along the roof &me-diately downstream from the valve.

c. Determine Elevation for Level Roof. Pressure required at vena contracta for minimum K to equal K_i is determined from equation for cavitation parameter (para 2-2b).

$$1.000 = \frac{P + 33}{51.14}$$

$$P = 18.14 \text{ ft}$$

Then the roof of the culvert must be at the elevation of the lower pool minus the pressure drop (table C-l, 120.00 - 106.7 = 13.30 ft), minus P , plus distance from vena contracta to roof of culvert (12.5 - depth of vena contracta) or el 120.00 - 13.30 - 18.14 + 12.5 - 4.96 = el 96.10. but factor of safety (para 2-3a, one-tenth lift) of 4.00 ft, should be subtracted and therefore culvert roof must not be higher than el 92.10.

d. Determine Elevation for Roof at Valve with Culvert Roof Downstream Sloped Up 5.0 ft (40% Expansion). From figure 2-1, $K_i = 0.470$. Loss coefficients in paragraph C-2 must be reevaluated and, for this example, become:

Intake	$0.200\ V^2/2g$
Upstream conduit	$0.050\ V^2/2g$
Downstream conduit	$0.320\ V^2/2g$
Chamber manifold	$0.630\ V^2/2g$
Total (valve open)	$1.300\ V^2/2g$

e. Develop New Hydraulic Data and Determine Elevation for Expanded Roof. Computations outlined in paragraphs C-3a and C-3b are repeated. Again K is minimum at a time of 1.4 min but at the vena contracta the pressure drop now is 18.4 ft and the velocity head is 55.48 ft. As in paragraph C-3c:

$$0.470 = \frac{P + 33}{55.48}$$

$$P = -6.92$$

Culvert roof at valve: el 120.00 - (-6.92) - 18.4 + 12.5 - 4.96 = el 116.06 - 4.0 (safety factor) = el 112.06

Since this would place the roof of the expanded culvert at el 117.06, less than 5 ft below lower pool, the culvert roof at the valve must not be higher than el 110, that required for minimum submergence.

f. Maximum Feasible Elevation for Culvert Roof. An expansion of 4.25 ft would result in the requirements for no cavitation plus the safety factor matching the criterion for minimum submergence of the culvert system and would place the culvert roof at the valves at the maximum feasible elevation of 110.75.

EXAMPLE 2

C-4. Data Previously Developed. Identical to Example 1 except upper pool at el 180 and thus lift of 60 ft.

C-5. Solution.

a. Level Roof. Computations as in Example 1 reveal that with a level roof and a safety factor of 6.0 ft (one-tenth lift) the culvert roof must be placed no higher than el 51.69 to provide submergence needed to prevent cavitation. An alternative would be to provide air vents downstream from the valve and place the culvert at an elevation where air will be drawn in the vents during the critical portion of the valve opening period. Computations have revealed that the pressure drop (lower pool to minimum gradient at vena contracta) would be 23.10 ft. Thus to provide the desired 10 ft of negative pressure on the roof (para 2-3a) the culvert roof should be 13.10 below lower pool or at el 106.90.

b. Roof Sloped Up 5 ft (40% Expansion). If the roof is sloped up 5 ft, loss coefficients are reevaluated as in paragraph C-3d and computations indicate that the roof of the culvert at the valves can be placed no higher than el 81.76 to meet submergence requirements for cavitation-free operation. In this case, if the alternative of providing air vents is adopted then the recomputed pressure drop, 31.80 ft, must be reduced by 58% (fig. 2-2) due to the 40% culvert expansion. Thus the pressure drop becomes 13.4 ft and to provide 10 ft of negative pressure would require placing the roof of the culvert at the valves only 3.4 ft below lower pool. Obviously, this does not meet minimum submergence requirements and expansion of the roof by 5 ft is not feasible for venting.

C-6. Maximum Feasible Elevation for Culvert Roof. For this example, a roof expansion of 2.75 ft would be optimum and would allow the vented roof of the culvert at the valve to be at el 112.25.